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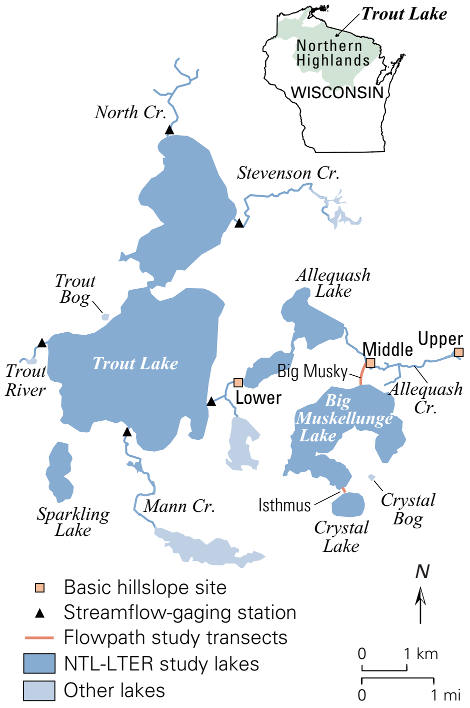
Trout Lake, Wisconsin

A Water, Energy, and Biogeochemical Budgets Program Site

The Trout Lake Watershed is in the Northern Highlands Lake District in north-central Wisconsin. The study area includes four subbasins with five lakes and two bog lakes. The objectives of the Trout Lake WEBB project are to (1) describe processes controlling water and solute fluxes in the Trout Lake watershed, (2) examine interactions among those processes and (3) improve the capability to predict changes in water and solute fluxes for a range of spatial and temporal scales (Elder and others, 1992).

The Trout Lake WEBB site is co-located with the National Science Foundation's North Temperate Lakes Long-Term Ecological Research (NTL–LTER) project (Magnuson and others, 1984). The Wisconsin WEBB research, which is concerned primarily with watershed processes, was designed to complement the NTL–LTER research that focuses primarily on in-lake processes.



Location of Trout Lake in Wisconsin, showing 3 basic hillslope sites, stream gages and flowpath study transects.

Nearly 80 percent of the land area and 60 percent of the lake frontage in the study area lie within two state forests. Many of the lakes in this area have watersheds that are completely forested with a mixture of coniferous and deciduous species. The surficial geology of the area is dominated by 30-50 meters of unconsolidated glacial outwash overlying Precambrian igneous bedrock. The glacial outwash is predominantly sand and nearly carbonate free, a characteristic that distinguishes the watershed from otherwise similar glacial lake districts in the upper Midwest and Canada. The soils are generally thin with high organic content in the uppermost horizon. The topography of the area is generally flat, with a total relief of less than 50 meters across the Trout Lake watershed.

Coarse surficial deposits and low relief combine to yield a predominance of lakes in the Northern Highland area that have no surface-water inlets or outlets, and have hydrologic budgets that are dominated by direct precipitation, evapotranspiration and ground-water flow. In addition, the highly conductive nature of the glacial outwash promotes effective exchange of water between the lakes and the ground-water system. One manifestation of the strong connectivity of the lakes and the ground-water system is the predominance of lake-water plumes that move through the surficial sediments.

Modeling of Ground-Water Systems

Because the water budget of the Trout Lake watershed is dominated by the ground-water system, it is critically important to develop comprehensive tools to characterize the movement of water and the solutes it carries through the watershed. Numerical models are commonly used to provide a better understanding of ground-water systems. A numerical ground-water model is a mathematical description of the physical ground-water system that can be used to solve for water levels and flow rates (fluxes) anywhere within the watershed boundaries. Because of the high density

The landscape in the Trout Lake WEBB study area is characterized by a moderately dense distribution of lakes.

THE WEBB PROGRAM

The Water, Energy, and Biogeochemical Budgets (WEBB) Program was started in 1991 at five small watersheds in the United States to examine water, energy, and biogeochemical fluxes and to determine the effects of atmospheric deposition, climatic variables, and human influences on watershed processes.

The five sites are at Loch Vale, Colorado; Luquillo Experimental Forest, Puerto Rico; Panola Mountain, Georgia; Sleepers River, Vermont; and Trout Lake, Wisconsin. These sites are supported, in part, by other programs in the USGS, other Federal and State Agencies, and Universities.

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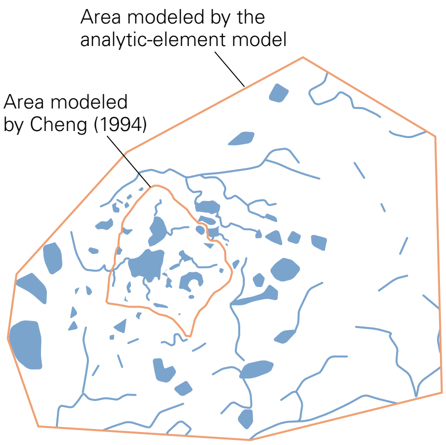


The area modeled by traditional finite-difference methods is within the larger domain of the analytic element model. Blue lines represent surface-water features (streams and lakes) that are modeled as sources/sinks in the analytic element model. Modeling an area larger than the watershed allows the watershed boundaries to be calculated rather than estimated.

of lakes in this area that are hydraulically connected to the ground-water system, these models also provide important information about lake hydrology.

One of the keys to understanding how water and energy flows through a system is knowledge of what happens at the boundaries of the watershed. Where the boundaries are located and how they interact with the watershed is crucial. Many times the ground-watershed boundaries are assumed to match closely the surface-watershed boundaries as defined by the topography of the landscape. In many cases, however, the boundaries of the ground-watershed and the surface-watershed do not align perfectly. This discrepancy can be important, especially in lake systems that have large ground-water interactions, such as the Trout Lake watershed. To address this factor, one focus of research efforts at the Trout Lake WEBB site has been the development of a numerical model of the ground-water system with an emphasis on better describing the boundaries of the watershed (Hunt and others, 1998). Previous NTL–LTER research resulted in a complex model of the Trout Lake watershed (Cheng, 1994) that is based on a traditional finite-difference modeling approach (complex FD model). The final model, which was calibrated against field measured water-levels in 31 observation wells and stream base-flow measurements in the 5 tributary streams to Trout Lake, resulted in a complex set of model parameters to describe the hydraulic characteristics of the system. A different modeling approach (analytic-element model) was used to refine the watershed boundaries. This approach was used primarily because it easily allowed the model area to be greatly expanded, and did not require dividing the model area into specified grid cells or specifying conditions at the model boundaries. The resulting analytic-element model used a less complex set of hydraulic characteristics than the traditional finite-difference model.

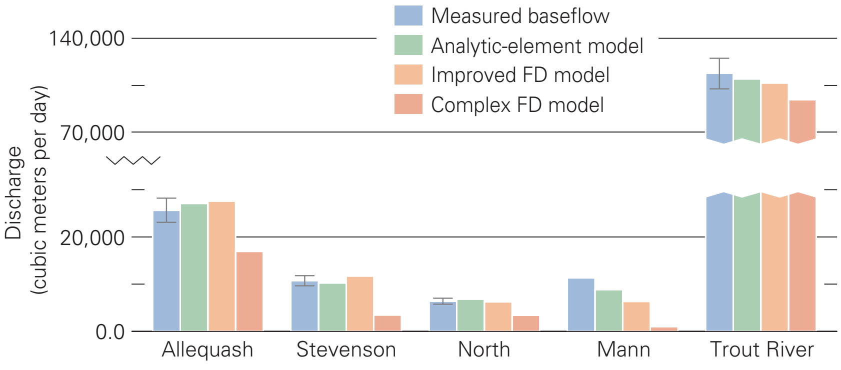
The use of an analytic-element model, combined with flow and hydraulic head measurements, permitted construction of an improved and simplified flow model.

The analytic-element model was used to calculate boundary fluxes for the original finite-difference-model grid used by Cheng (1994). The improved finite-difference model that resulted was less complex (Hunt and others, 1998). The differences in the observed and modeled water levels were similar for all three of the calibrations. The simulated stream fluxes, for both the analytic-element model and the improved finite-difference model, however, are much improved over the traditional model.

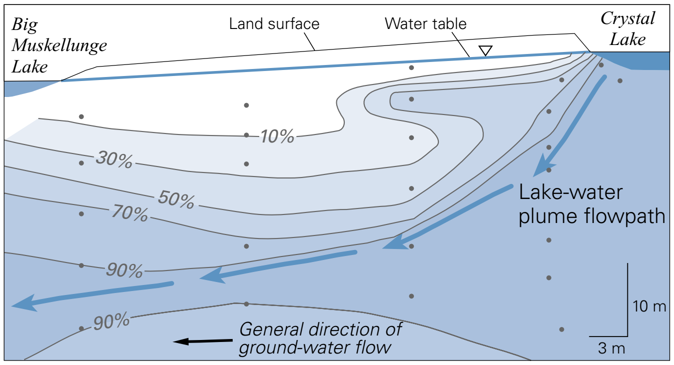
Water Sources and Flow Paths

To understand the chemistry of lakes, one must first understand where the water comes from, how it travels, and what happens chemically along its flowpath. In the Trout Lake watershed, there are two major sources of water to the ground-water system: precipitation recharge through the upland areas (terrestrial recharge) and recharge from upgradient surface-water features (lake recharge). Thus, the water budget and solute composition of lakes and streams at various points downgradient in the watershed will depend upon the relative contributions from these two sources. The goal of this research is to combine the knowledge of chemical reactions along each type of ground-water flowpath, with the knowledge of flowpaths obtained from the ground-water-modeling work to develop a watershed-scale model of solute flux.

The stable isotopes of water ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) are commonly used as hydrologic tracers. Because evaporation selectively removes the lighter isotopes (^{16}O and ^{1}H), surface-water bodies become “enriched” in the heavier isotopes (^{18}O and ^{2}H) and are generally distinguishable from precipitation (rain and snow). In the Trout Lake watershed, ground-water derived through terrestrial recharge has a relatively “light” isotopic composition, and is very different than the “heavy” isotopic composition of the lakes. Because the hydrologic budgets are dominated by precipitation, evaporation and ground water, the Trout Lake WEBB site is an ideal location for using stable isotopes to determine the source location and timing of subsurface flowpaths in this watershed.



Simulated and measured base-flow stream fluxes for the five streams tributary to Trout Lake. The estimated error for the measured baseflow is indicated by error bars (±10 percent); the Mann Creek streamflow is estimated using the Allequash record, and the measurement error is likely greater than 10 percent. By improving the accuracy of the watershed boundaries, the accuracy of the stream flux and its distribution across the watershed is much improved.



Lines of equal percentages of Crystal Lake water in observation wells (grey dots) that are located beneath the isthmus between Crystal Lake and Big Muskellunge Lake. The lake-water plume flowpath is based on the large difference between the water isotope compositions of O and H in lake- and terrestrial-recharge water.

Two flowpath studies are being conducted at the Trout Lake WEBB site—a transect between Crystal Lake and Big Muskellunge Lake (Isthmus) and a substantially longer transect between Big Muskellunge Lake and Allequash Creek (Big Musky). For the Isthmus study, water isotopes were used to delineate the dominant flowpath originating from the littoral zone in Crystal Lake, based on the proportion of Crystal Lake water in the observation wells (Bullen and others, 1996). A similar distinction between the two water sources can be seen along the Big Musky transect; in both cases the large difference in water isotopes greatly enhances delineation of flowpaths, and aids in the calibration of the ground-water-flow model of the system. Note that the flowpath from the Crystal Lake littoral zone does not lead to Big Muskellunge Lake; it continues downgradient under the lake. This result is somewhat counter intuitive because Big Muskellunge is at a lower elevation than Crystal Lake. In this case the position of the lakes in the overall flow system has a striking influence on the flowpaths.

The use of water isotopes has helped to distinguish water sources for flowpaths that range in length from several meters to about 1 kilometer (watershed scale). Establishing a reliable flowpath increases the confidence of results in related studies, such as determining the geochemical evolution within the watershed.

In addition to the water isotopes along the Isthmus, a focus of our research is to discern where the water gets its solutes—that is, the weathering of minerals. Strontium isotopes ($^{87}Sr/^{86}Sr$) were used together with solute chemistry to identify the chemical reactions that control ground-water chemistry along this flowpath. The striking conclusion from the study is that the mineral weathering (as shown by the wide range of $^{87}Sr/^{86}Sr$) depended on whether the water came from terrestrial or lake recharge. For terrestrial recharge, the weathering is dominated by K-feldspar and/or biotite, whereas the lake recharge water is dominated by dissolution of plagioclase. Because the $^{87}Sr/^{86}Sr$ signature is maintained along the different flowpaths, the combined use of strontium and water isotopes provides a powerful tool for discerning the source of waters and solutes in the Trout Lake watershed (Bullen and others, 1996). The Sr isotopes also demonstrated that the source of solutes can change along a flowpath even though mineral composition of the sediments does not change. Geochemical reaction-path models must include this phenomenon to describe adequately the chemical evolution of ground water along a flowpath.

In general, more chemical change of bioreactive species occurs over the last 10 to 20 centimeters of the hyporheic zone than occurs over a flow path of 100's of meters through the watershed. The nutrient status of lakes and streams is, therefore, largely regulated by the biogeochemical reactions at the sediment-water interface.

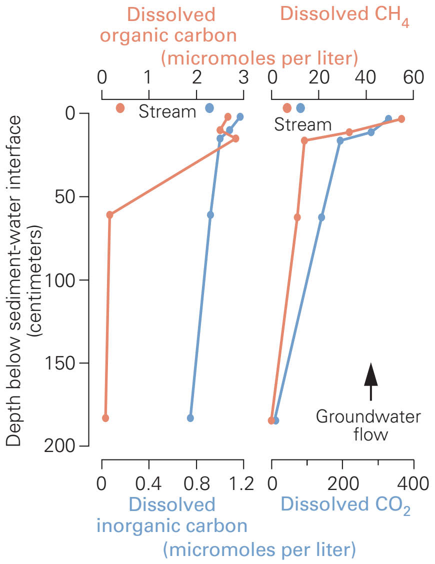
Biogeochemical Processes at the Sediment-Water Interface

Several studies in the Trout Lake area have demonstrated that small-scale processes operating near the sediment-water interface have a controlling influence on the chemistry—and subsequently the biology—of lakes and streams. Although biogeochemical processes occur throughout watersheds, the sediment-water interface is a zone of intense bioreactivity and is particularly important for regulating the transport of bioreactive chemical species, including nutrients (carbon, nitrogen, phosphorus and sulfur) and other trace elements. Because one of the goals of WEBB research is to further our understanding of biogeochemical fluxes within watersheds, it is crucial to understand the processes that occur at the sediment-water interface.

An emphasis of research at the Trout Lake WEBB site focuses on the biogeochemical processes that operate in the hyporheic zone. The hyporheic zone in this study is defined as the area under the streambed where distinct chemical changes in upwelling ground water begin to occur. In a recent study, the hyporheic zone was sampled at the upper, middle and lower sites of Allequash Creek at a fine vertical scale, with increments as little as 5 centimeters (Schindler and Krabbenhoft, 1998). The most striking feature of the profiles immediately under the stream is the dramatic increase in all chemical constituent concentrations as the water moves upward through the hyporheic zone, yet the corresponding chemical constituent concentrations in the stream water are much lower than those in the hyporheic water. The apparent loss of bioreactive constituents in the stream, such as CO_2 and CH_4, as the hyporheic pore water discharges to the stream, is attributed to biologic uptake, oxidation and evasion to the atmosphere. If the dissolved organic carbon being produced in the hyporheic zone and lost in the stream is being used by bacteria and algae, the biological productivity of these stream systems is larger than commonly thought. Additional research is ongoing at the three sites and in additional streams in the Trout Lake watershed to further understand the mechanisms that cause these important processes.

—John F. Walker and Thomas D. Bullen

This portable sampling device allows centimeter-scale-depth sampling of the pore waters beneath the sediment-water interface of lakes and streams.



Streambed depth profiles for carbon-related chemical constituents in the hyporheic zone beneath the middle site along Allequash Creek. A depth of zero centimeters marks the sediment-water interface. Large increases in chemical constituent concentrations occur over a small depth just before the ground water discharges to the stream. For some bioreactive solutes the increases in concentration near the sediment-water interface can be much larger those in the deeper and longer groundwater flowpath.

SUMMARY

- Combining an analytic-element model with traditional hydraulic measurements allows construction of an improved, simplified groundwater-flow model.
- A reasonable understanding of water sources and flowpaths can be accomplished with the combined use of water isotopes, strontium isotopes and traditional hydraulic measurements. With this approach, reliable prediction of flowpaths that range from several meters to nearly a kilometer can be made; these results are helpful for related studies, such as determining the geochemical evolution within a watershed.
- The sediment-water interface in streambeds—where ground water interacts with stream water—plays a major role in the carbon cycling in a watershed.

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COLLABORATORS

Scientists with the WEBB research program at Trout Lake have collaborated with faculty members at the University of Wisconsin-Madison, Dartmouth College and Northern Michigan University. Several students at the University of Wisconsin-Madison have contributed to the WEBB project through their thesis research at the site. The WEBB program works closely with the National Science Foundation Long-Term Ecological Research (LTER) program in the Trout Lake watershed through the sharing of data and ideas and through the publication of research papers together.

For more information about the Trout Lake Research Watershed WEBB study visit:

http://infotrek.er.usgs.gov/doc/webb/

For more information or for reprints, please contact:

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